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## Frequent mutations in chromatin-remodelling genes in pulmonary carcinoids

Fernandez-Cuesta, Lynnette ; Peifer, Martin ; Lu, Xin ; et al ; Soltermann, Alex

**Abstract:** Pulmonary carcinoids are rare neuroendocrine tumours of the lung. The molecular alterations underlying the pathogenesis of these tumours have not been systematically studied so far. Here we perform gene copy number analysis (n=54), genome/exome (n=44) and transcriptome (n=69) sequencing of pulmonary carcinoids and observe frequent mutations in chromatin-remodelling genes. Covalent histone modifiers and subunits of the SWI/SNF complex are mutated in 40 and 22.2% of the cases, respectively, with MEN1, PSIP1 and ARID1A being recurrently affected. In contrast to small-cell lung cancer and large-cell neuroendocrine lung tumours, TP53 and RB1 mutations are rare events, suggesting that pulmonary carcinoids are not early progenitor lesions of the highly aggressive lung neuroendocrine tumours but arise through independent cellular mechanisms. These data also suggest that inactivation of chromatin-remodelling genes is sufficient to drive transformation in pulmonary carcinoids.

DOI: <https://doi.org/10.1038/ncomms4518>

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ZORA URL: <https://doi.org/10.5167/uzh-96318>

Journal Article

Published Version



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Originally published at:

Fernandez-Cuesta, Lynnette; Peifer, Martin; Lu, Xin; et al; Soltermann, Alex (2014). Frequent mutations in chromatin-remodelling genes in pulmonary carcinoids. *Nature Communications*, 5:3518.

DOI: <https://doi.org/10.1038/ncomms4518>

## ARTICLE

Received 13 Aug 2013 | Accepted 26 Feb 2014 | Published 27 Mar 2014

DOI: 10.1038/ncomms4518

# Frequent mutations in chromatin-remodelling genes in pulmonary carcinoids

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Pulmonary carcinoids are rare neuroendocrine tumours of the lung. The molecular alterations underlying the pathogenesis of these tumours have not been systematically studied so far. Here we perform gene copy number analysis ( $n = 54$ ), genome/exome ( $n = 44$ ) and transcriptome ( $n = 69$ ) sequencing of pulmonary carcinoids and observe frequent mutations in chromatin-remodelling genes. Covalent histone modifiers and subunits of the SWI/SNF complex are mutated in 40 and 22.2% of the cases, respectively, with *MEN1*, *PSIP1* and *ARID1A* being recurrently affected. In contrast to small-cell lung cancer and large-cell neuroendocrine lung tumours, *TP53* and *RB1* mutations are rare events, suggesting that pulmonary carcinoids are not early progenitor lesions of the highly aggressive lung neuroendocrine tumours but arise through independent cellular mechanisms. These data also suggest that inactivation of chromatin-remodelling genes is sufficient to drive transformation in pulmonary carcinoids.

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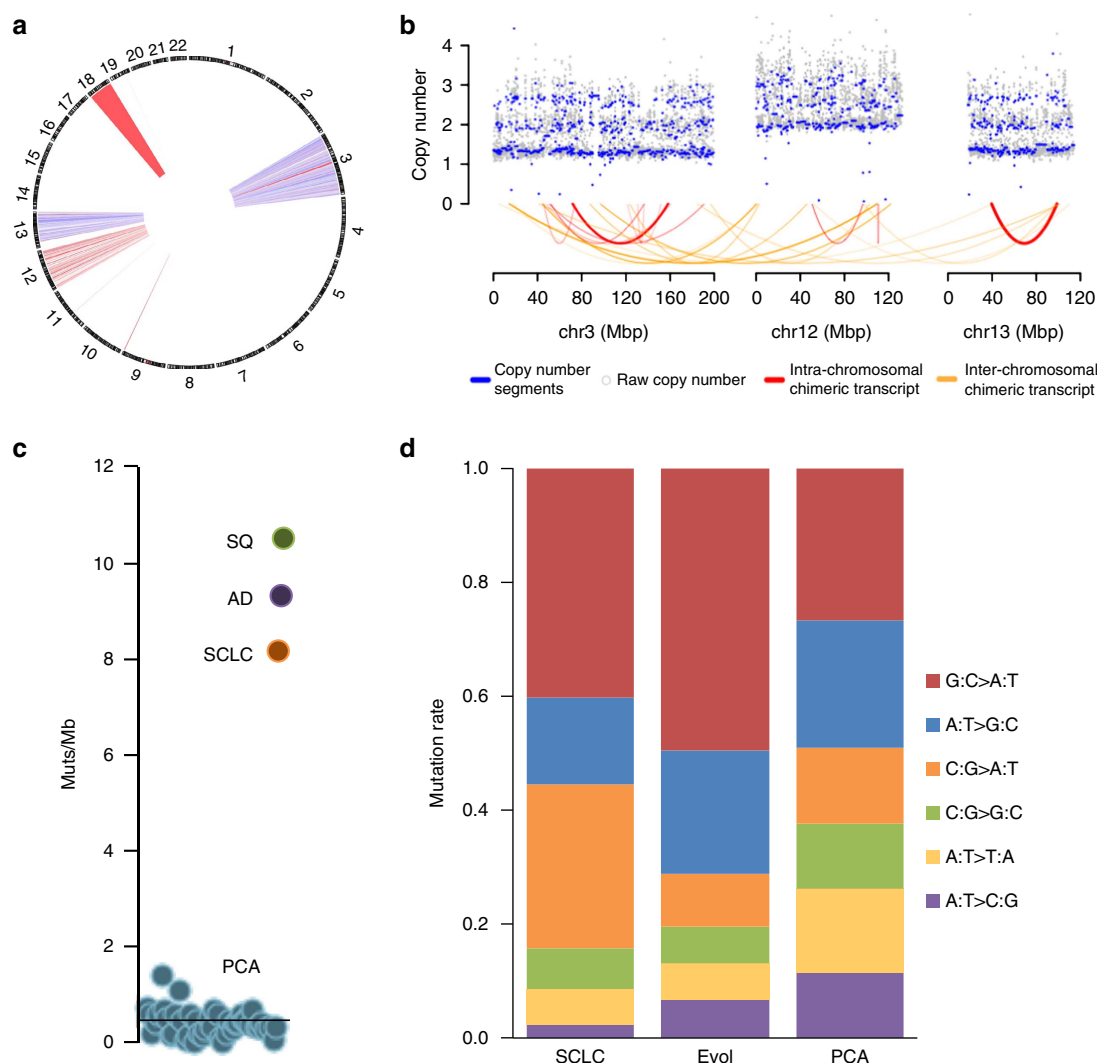
**P**ulmonary carcinoids are neuroendocrine tumours that account for about 2% of pulmonary neoplasms. On the basis of the WHO classification of 2004, carcinoids can be subdivided into typical or atypical, the latter ones being very rare (about 0.2%)<sup>1</sup>. Most carcinoids can be cured by surgery; however, inoperable tumours are mostly insensitive to chemo- and radiation therapies<sup>1</sup>. Apart from few low-frequency alterations, such as mutations in *MEN1* (ref. 1), comprehensive genome analyses of this tumour type have so far been lacking.

Here we conduct integrated genome analyses<sup>2</sup> on data from chromosomal gene copy number of 54 tumours, genome and exome sequencing of 29 and 15 tumour-normal pairs, respectively, as well as transcriptome sequencing of 69 tumours. Chromatin-remodelling is the most frequently mutated pathway in pulmonary carcinoids; the genes *MEN1*, *PSIP1* and *ARID1A* were recurrently affected by mutations. Specifically, covalent histone modifiers and subunits of the SWI/SNF (SWIh/Sucose

NonFermentable) complex are mutated in 40 and 22.2% of the cases, respectively. By contrast, mutations of *TP53* and *RB1* are only found in 2 out of 45 cases, suggesting that these genes are not main drivers in pulmonary carcinoids.

## Results

In total, we generated genome/exome sequencing data for 44 independent tumour-normal pairs, and for most of them, also RNAseq ( $n = 39$ , 69 in total) and SNP 6.0 ( $n = 29$ , 54 in total) data (Supplementary Table 1). Although no significant focal copy number alterations were observed across the tumours analysed, we detected a copy number pattern compatible with chromothripsis<sup>3</sup> in a stage-III atypical carcinoid of a former smoker (Fig. 1a; Supplementary Fig. 1). The intensely clustered genomic structural alterations found in this sample were restricted to chromosomes 3, 12 and 13, and led to the

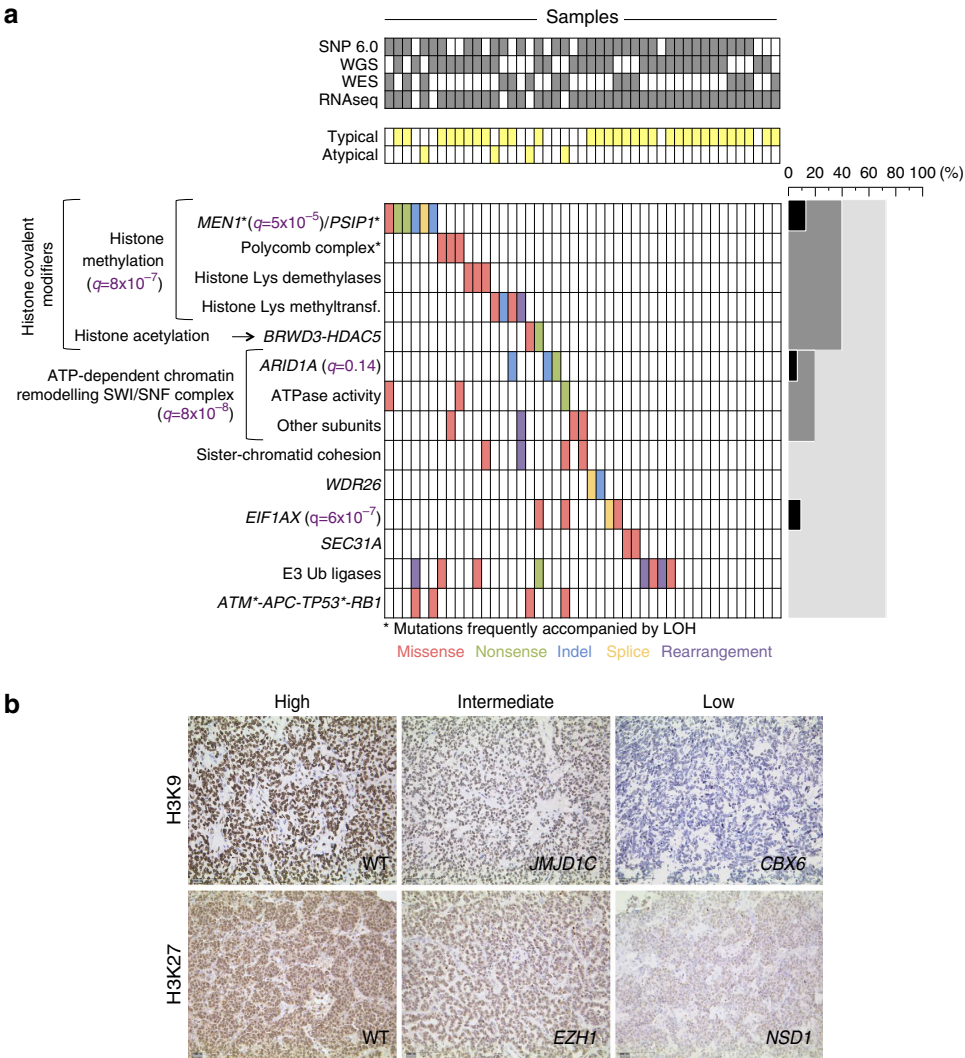


**Figure 1 | Genomic characterization of pulmonary carcinoids.** (a) CIRCOS plot of the chromothripsis case. The outer ring shows chromosomes arranged end to end. Somatic copy number alterations (gains in red and losses in blue) detected by 6.0 SNP arrays are depicted in the inside ring. (b) Copy numbers and chimeric transcripts of affected chromosomes. Segmented copy number states (blue points) are shown together with raw copy number data averaged over 50 adjacent probes (grey points). To show the different levels of strength for the identified chimeric transcripts, all curves are scaled according to the sequencing coverage at the fusion point. (c) Mutation frequency detected by genome and exome sequencing in pulmonary carcinoids (PCA). Each blue dot represents the number of mutations (mut) per Mb in one pulmonary carcinoid sample. Average frequencies are also shown for adenocarcinomas (AD), squamous (SQ) and small-cell lung cancer (SCLC) based on previous studies<sup>2,4,5</sup>. (d) Comparison of context-independent transversion and transition rates (an overall strand symmetry is assumed) between rates derived from molecular evolution (evol)<sup>36</sup>, from a previous SCLC sequencing study<sup>2</sup> and from the PCA genome and exome sequencing. All rates are scaled such that their overall sum is 1.

expression of several chimeric transcripts (Fig. 1b; Supplementary Table 2). Some of these chimeric transcripts affected genes involved in chromatin-remodelling processes, including out-of-frame fusion transcripts disrupting the genes *ARID2*, *SETD1B* and *STAG1*. Through the analyses of genome and exome sequencing data, we detected 529 non-synonymous mutations in 494 genes, which translates to a mean somatic mutation rate of 0.4 mutations per megabase (Mb) (Fig. 1c; Supplementary Data 1), which is much lower than the rate observed in other lung tumours (Fig. 1c)<sup>2,4,5</sup>. As expected, and in contrast to small-cell lung cancer (SCLC), no smoking-related mutation signature was observed in the mutation pattern of pulmonary carcinoids (Fig. 1d).

We identified *MEN1*, *ARID1A* and *EIF1AX* as significantly mutated genes<sup>2</sup> ( $q$ -value  $<0.2$ , see Methods section) (Fig. 2a; Supplementary Tables 1 and 3; Supplementary Data 1). *MEN1* and *ARID1A* play important roles in chromatin-remodelling processes. The tumour suppressor *MEN1* physically interacts with *MLL* and *MLL2* to induce gene transcription<sup>6</sup>. Specifically,

*MEN1* is a molecular adaptor that physically links *MLL* with the chromatin-associated protein *PSIP1*, an interaction that is required for *MLL/MEN1*-dependent functions<sup>7</sup>. *MEN1* also acts as a transcriptional repressor through the interaction with *SUV39H1*<sup>8</sup>. We observed mutually exclusive frame-shift and truncating mutations in *MEN1* and *PSIP1* in six cases (13.3%), which were almost all accompanied by loss of heterozygosity (Supplementary Fig. 2). We also detected mutations in histone methyltransferases (*SETD1B*, *SETDB1* and *NSD1*) and demethylases (*KDM4A*, *PHF8* and *JMJD1C*), as well as in the following members of the Polycomb complex<sup>9</sup> (Supplementary Tables 1 and 2; Supplementary Data 1): *CBX6*, which belongs to the Polycomb repressive complex 1 (PRC1); *EZH1*, which is part of the PRC2; and *YY1*, a member of the PHO repressive complex 1 that recruits PRC1 and PRC2. *CBX6* and *EZH1* mutations were also accompanied by loss of heterozygosity (Supplementary Fig. 2). In addition, we also detected mutations in the histone modifiers *BRWD3* and *HDAC5* in one sample each. In total, 40% of the cases carried mutually exclusive mutations in genes that are



**Figure 2 | Significant affected genes and pathways in pulmonary carcinoids.** (a) Significantly mutated genes and pathways identified by genome ( $n=29$ ), exome ( $n=15$ ) and transcriptome ( $n=69$ ) sequencing. The percentage of pulmonary carcinoids with a specific gene or pathway mutated is noted at the right side. The  $q$ -values of the significantly mutated genes and pathways are shown in brackets (see Methods section). Samples are displayed as columns and arranged to emphasize mutually exclusive mutations. (b) Methylation levels of H3K9me3 and H3K27me3 in pulmonary carcinoids. Representative pictures of different degrees of methylation (high, intermediate and low) for some of the samples summarized in Table 1. The mutated gene is shown in italics at the bottom right part of the correspondent picture. Wild-type samples are denoted by WT.

involved in covalent histone modifications ( $q$ -value =  $8 \times 10^{-7}$ , see Methods section) (Fig. 2a; Supplementary Table 4). To evaluate the impact of these mutations on histone methylation, we compared the levels of the H3K9me3 and H3K27me3 on seven mutated and six wild-type samples, and observed a trend towards lower methylation in the mutated cases (Fig. 2b; Table 1). Truncating and frame-shift mutations in *ARID1A* were detected in three cases (6.7%). *ARID1A* is one of the two mutually exclusive *ARID1* subunits, believed to provide specificity to the ATP-dependent SWI/SNF chromatin-remodelling complex<sup>10,11</sup>. Truncating mutations of this gene have been reported at high frequency in several primary human cancers<sup>12</sup>. In total, members of this complex were mutated in mutually exclusive fashion in 22.2% of the specimens ( $q$ -value =  $8 \times 10^{-8}$ , see Methods section) (Fig. 2a; Supplementary Table 4). Among them were the core subunits *SMARCA1*, *SMARCA2* and *SMARCA4*, which carry the ATPase activity of the complex, as well as the subunits *ARID2*, *SMARCC2*, *SMARCB1* and *BCL11A* (Fig. 2a; Supplementary Tables 1 and 2; Supplementary Data 1)<sup>13,14</sup>. Another recurrently affected pathway was sister-chromatid cohesion during cell cycle progression with the following genes mutated (Fig. 2a; Supplementary Tables 1 and 2; Supplementary Data 1; Supplementary Fig. 3): the cohesin subunit *STAG1* (ref. 15), the cohesin loader *NIPBL*<sup>16</sup>, the ribonuclease and microRNA processor *DICER*, necessary for centromere establishment<sup>17</sup>; and *ERCC6L*, involved in sister-chromatid separation<sup>18</sup>. In addition, although only few chimeric transcripts were detected in the 69 transcriptomes analysed (Supplementary Table 5), we found one sample harbouring an inactivating chimeric transcript, leading to the loss of the mediator complex gene *MED24* (Supplementary Fig. 4) that interacts both physically and functionally with cohesin and *NIPBL* to regulate gene expression<sup>19</sup>. In summary, we detected mutations in chromatin-remodelling genes in 23 (51.1%) of the samples analysed. The specific role of histone modifiers in the development of pulmonary carcinoids was confirmed by the lack of significance of these pathways in SCLC<sup>2</sup> (Supplementary Table 4). This was further supported by a gene expression analysis including 49 lung adenocarcinomas (unpublished data), 43 SCLC<sup>2,20</sup> and the 69 pulmonary carcinoids included in this study (Supplementary Data 2). Consensus k-means clustering revealed that although both SCLC and pulmonary carcinoids are lung neuroendocrine tumours, both tumour types as well as

adenocarcinomas formed statistically significant separate clusters (Fig. 3a). In support of this notion, we recently reported that the early alterations in SCLC universally affect *TP53* and *RB1*<sup>2</sup>, whereas in this study these genes were only mutated in two samples (Fig. 2a; Supplementary Table 1; Supplementary Data 1). Moreover, when examining up- and downregulated pathways in SCLC versus pulmonary carcinoids by gene set enrichment analysis<sup>21</sup>, we found that in line with the pattern of mutations, the *RB1* pathway was statistically significantly altered in SCLC ( $q$ -value =  $5 \times 10^{-4}$ , see Methods section) but not in pulmonary carcinoids (Fig. 3b; Supplementary Table 6).

Another statistically significant mutated gene was the eukaryotic translation initiation factor 1A (*EIF1AX*) mutated in four cases (8.9%). In addition, *SEC31A*, *WDR26* and the E3 ubiquitin ligase *HERC2* were mutated in two samples each. Further supporting a role of E3 ubiquitin ligases in the development of pulmonary carcinoids, we found mutations or rearrangements affecting these genes in 17.8% of the samples analysed (Fig. 2a; Supplementary Tables 1 and 7; Supplementary Data 1). All together, we have identified candidate *driver* genes in 73.3% of the cases. Of note, we did not observe any genetic segregation between typical or atypical carcinoids, neither between the expression clusters generated from the two subtypes, nor between these clusters and the mutated pathways (Supplementary Fig. 5). However, it is worth mentioning that only nine atypical cases were included in this study. The spectrum of mutations found in the discovery cohort was further validated by transcriptome sequencing of an independent set of pulmonary carcinoid specimens (Supplementary Tables 1 and 8). Owing to the fact that many nonsense and frame-shift mutations may result in nonsense-mediated decay<sup>22,23</sup>, the mutations detected by transcriptome sequencing were only missense. Owing to this bias, accurate mutation frequencies could not be inferred from these data.

Discussion

This study defines recurrently mutated sets of genes in pulmonary carcinoids. The fact that almost all of the reported genes were mutated in a mutually exclusive manner and affected a small set of cellular pathways defines these as the key pathways in this tumour type. Given the frequent mutations affecting the few signalling pathways described above and the almost universal absence of other cancer mutations, our findings support a model where pulmonary carcinoids are not early progenitor lesions of other neuroendocrine tumours, such as SCLC or large-cell neuroendocrine carcinoma, but arise through independent cellular mechanisms. More broadly, our data suggest that mutations in chromatin-remodelling genes, which in recent studies were found frequently mutated across multiple malignant tumours<sup>24</sup>, are sufficient to drive early steps in tumorigenesis in a precisely defined spectrum of required cellular pathways.

Methods

**Tumour specimens.** The study as well as written informed consent documents had been approved by the Institutional Review Board of the University of Cologne. Additional biospecimens for this study were obtained from the Victorian Cancer Biobank, Melbourne, Australia; the Vanderbilt-Ingram Cancer Center, Nashville, Tennessee, USA; and Roy Castle Lung Cancer Research Programme, The University of Liverpool Cancer Research Center, Liverpool, UK. The Institutional Review Board of each participating institution approved collection and use of all patient specimens in this study.

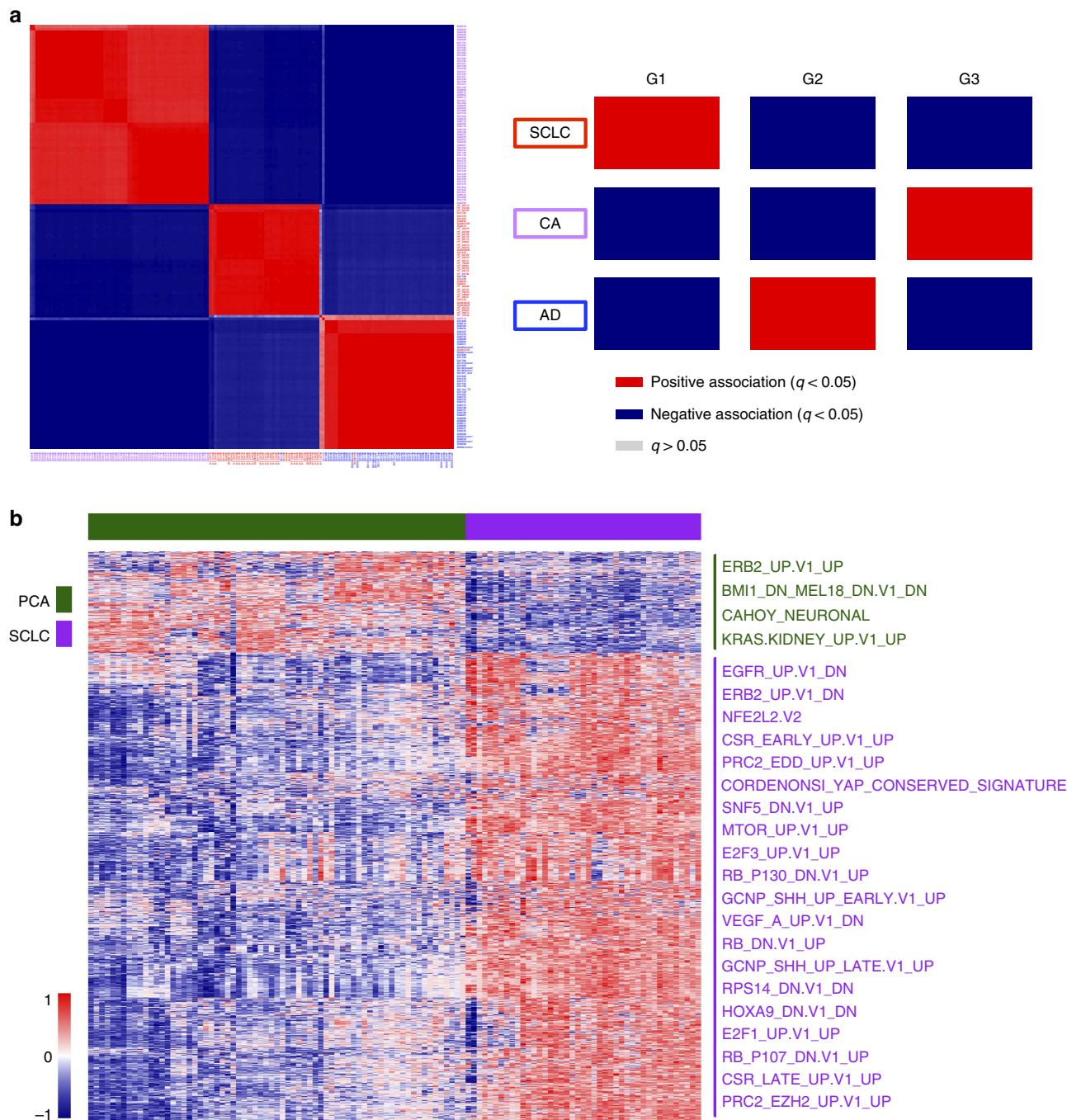
**Nucleic acid extraction and sample sequencing.** All samples in this study were reviewed by expert pathologists. Total RNA and DNA were obtained from fresh-frozen tumour and matched fresh-frozen normal tissue or blood. Tissue was frozen within 30 min after surgery and was stored at  $-80^{\circ}\text{C}$ . Blood was collected in tubes containing the anticoagulant EDTA and was stored at  $-80^{\circ}\text{C}$ . Total DNA and RNA were extracted from fresh-frozen lung tumour tissue containing more than

Table 1 | Overview of samples annotated for mutations in genes involved in histone methylation and correspondent levels of H3K9me3 and H3K27me3 detected by immunohistochemistry.

Sample	Mutation	H3K9me3	H3K27me3
S02333	<i>JMJD1C</i> _H954N	Intermediate	Low
S01502	<i>KDM4A</i> _I168T	Intermediate	NA
S02323	<i>MEN1</i> _e3 + 1 and LOH	Low	Low
S02339	<i>NSD1</i> _A1047G	Intermediate	Low
S02327	<i>CBX6</i> _P302S and LOH	Low	Low
S01746	<i>EZH1</i> _R728G and LOH	Low	Intermediate
S02325	<i>YY1</i> _E253K	Low	Intermediate
S01501	Wild type	NA	High
S01731	Wild type	Low	Low
S01742	Wild type	High	High
S02334	Wild type	Intermediate	High
S02337	Wild type	High	High
S02338	Wild type	High	Intermediate

LOH, loss of heterozygosity; NA, not applicable.





**Figure 3 | Expression data analysis of pulmonary carcinomas based on RNAseq data.** (a) Consensus k-means clustering<sup>32,33</sup> using RNAseq expression data of 49 adenocarcinomas (AD, in blue), 43 small-cell lung cancer (SCLC, in red) and 69 pulmonary carcinoids (PCA, in purple) identified three groups using the clustering module from GenePattern<sup>31</sup> and consensus CDF<sup>32,33</sup> (left panel). The significance of the clustering was evaluated by using SigClust<sup>34</sup> with a  $P < 0.0001$ . Fisher's exact test<sup>35</sup> was used to check associations between the clusters and the histological subtypes (right panel). (b) Gene set enrichment analysis<sup>21</sup> for SCLC versus PCA using RNAseq expression data. Low gene expression is indicated in blue and high expression, in red. On the right side are given the altered pathways in PCA (green) and SCLC (purple).

70% tumour cells. Depending on the size of the tissue, 15–30 sections, each 20  $\mu\text{m}$  thick, were cut using a cryostat (Leica) at  $-20^\circ\text{C}$ . The matched normal sample obtained from frozen tissue was treated accordingly. DNA from sections and blood was extracted using the Puregene Extraction kit (Qiagen) according to the manufacturer's instructions. DNA was eluted in  $1 \times \text{TE}$  buffer (Qiagen), diluted to a working concentration of  $150 \text{ ng } \mu\text{l}^{-1}$  and stored at  $-80^\circ\text{C}$ . For whole exome sequencing, we fragmented  $1 \mu\text{g}$  of DNA with sonification technology (Bioruptor, diagenode, Liège, Belgium). The fragments were end repaired and adaptor ligated, including incorporation of sample index barcodes. After size selection, we subjected the library to an enrichment process with the SeqCap EZ Human Exome Library

version 2.0 kit (Roche NimbleGen, Madison, WI, USA). The final libraries were sequenced with a paired-end  $2 \times 100 \text{ bp}$  protocol. On average, 7 Gb of sequence were produced per normal, resulting in  $30 \times$  coverage of more than 80% of target sequences (44 Mb). For better sensitivity, tumours were sequenced with 12 Gb and  $30 \times$  coverage of more than 90% of target sequences. We filtered primary data according to signal purity with the Illumina Realtime Analysis software. Whole-genome sequencing was also performed using a read length of  $2 \times 100 \text{ bp}$  for all samples. On average, 110 Gb of sequence were produced per sample, aiming a mean coverage of  $30 \times$  for both tumour and matched normal. RNAseq was performed on complementary DNA libraries prepared from PolyA + RNA extracted

from tumour cells using the Illumina TruSeq protocol for mRNA. The final libraries were sequenced with a paired-end  $2 \times 100$  bp protocol aiming at 8.5 Gb per sample, resulting on a  $30 \times$  mean coverage of the annotated transcriptome. All the sequencing was carried on an Illumina HiSeq 2000 sequencing instrument (Illumina, San Diego, CA, USA).

**Sequence data processing and mutation detection.** Raw sequencing data are aligned to the most recent build of the human genome (NCBI build 37/hg19) using BWA (version: 0.5.9rc1)<sup>25</sup> and possible PCR duplicates are subsequently removed from the alignments. Somatic mutations were detected using our in-house-developed sequencing analysis pipeline. In brief, the mutation-calling algorithm incorporates parameters such as local copy number profiles, estimates of tumour purity and ploidy, local sequencing depth, as well as the global sequencing error into a statistical model with which the presence of a mutated allele in the tumour is determined. Next, the absence of this variant in the matched normal is assessed by demanding that the corresponding allelic fraction is compatible with the estimated background sequencing error in the normal. In addition, we demand that the allelic fractions between tumour and normal differ significantly. To finally remove artificial mutation calls, we apply a filter that is based on the forward–reverse bias of the sequencing reads. Further details of this approach are given in Peifer *et al.*<sup>2</sup>

**Genomic rearrangement reconstruction from paired-end data.** To reconstruct rearrangements from paired-end data, we refined our initial method<sup>2</sup> by adding breakpoint-spanning reads. Here, locations of encompassing read pairs are screened for further reads where only one pair aligns to the region and the other pair either does not align at all or is clipped by the aligner. These reads are then realigned using BLAT to a 1,000 bp region around the region defined by the encompassing reads. Rearrangements confirmed by at least one spanning read are finally reported. To filter for somatic rearrangements, we subtracted those regions where rearrangements are present in the matched normal and in all other sequenced normals within the project.

**Analysis of significantly mutated genes and pathways.** The analysis of significantly mutated genes is done in a way that both gene expression and the accumulation of synonymous mutations are considered to obtain robust assessments of frequently mutated, yet biologically relevant genes. To this end, the overall background mutation rate is determined first, from which the expected number of mutations for each gene is computed under the assumption of a purely random mutational process. This gene-specific expected number of mutations defines the underlying null model of our statistical test. To account for misspecifications, for example, due to a local variation of mutation rates, we also incorporated the synonymous to non-synonymous ratio into a combined statistical model to determine significantly mutated genes. Since mutation rates in non-expressed genes are often high than the genome-wide background rate<sup>2,26</sup>, genes that are having a median Fragments Per Kilobase of transcript per Million fragments mapped (FPKM) value  $< 1$  in our transcriptome sequencing data are removed prior testing. To account for multiple hypothesis testing, we are using the Benjamini–Hochberg approach<sup>27</sup>. Mutation data of the total of 44 samples, for which either whole-exome sequencing (WES) or whole-genome sequencing (WGS) was performed, were used for this analysis.

In case of the pathway analysis, gene lists of the methylation and the SWI/SNF complex were obtained from recent publications<sup>9,13,14,28</sup>. To assess whether mutations in these pathways are significantly enriched, all genes of the pathway are grouped together as if they represent a ‘single gene’ and subsequently tested if the total number of mutation exceed mutational background of the entire pathway. To this end, the same method as described above was used. Mutation data of the total of 44 samples, for which either WES or WGS was performed, were used for this analysis.

**Analysis of chromosomal gene copy number data.** Hybridization of the Affymetrix SNP 6.0 arrays was carried out according to the manufacturers’ instructions and analysed as follows: raw signal intensities were processed by applying a log-linear model to determine allele-specific probe affinities and probe-specific background intensities. To calibrate the model, a Gauss–Newton approach was used and the resulting raw copy number profiles are segmented by applying the circular binary segmentation method<sup>29</sup>.

**Analysis of RNAseq data.** For the analysis of RNAseq data, we have developed a pipeline that affords accurate and efficient mapping and downstream analysis of transcribed genes in cancer samples (Lynette Fernandez-Cuesta and Ruping Sun, personal communication). In brief, paired-end RNAseq reads were mapped onto hg19 using a sensitive gapped aligner, GSNAP<sup>30</sup>. Possible breakpoints were called by identifying individual reads showing split-mapping to distinct locations as well as clusters of discordant read pairs. Breakpoint assembly was performed to leverage information across reads anchored around potential breakpoints. Assembled contigs were aligned back to the reference genome to confirm *bona fide* fusion points.

**Dideoxy sequencing.** All non-synonymous mutations found in the genome/exome data were checked in RNAseq data when available. Genes recurrently mutated involved in pathways statistically significantly mutated, or interesting because of their presence in other lung neuroendocrine tumours, were selected for validation. One hundred and fifty eight mutations were considered for validation: 115 validated and 43 did not (validation rate 73%). Sequencing primer pairs were designed to enclose the putative mutation (Supplementary Data 1), or to encompass the candidate rearrangement (Supplementary Table 7) or chimeric transcript (Supplementary Table 2 and 5). Sequencing was carried out using dideoxy-nucleotide chain termination (Sanger) sequencing, and electropherograms were analysed by visual inspection using four Peaks.

**Gene expression data analyses.** Unsupervised consensus clustering was applied to RNAseq data of 69 pulmonary carcinoids, 49 adenocarcinomas and 43 SCLC<sup>2,20</sup> samples. The 3,000 genes with highest variation across all samples were filtered out before performing consensus clustering. We used the clustering module from GenePattern<sup>31</sup> and the consensus CDF<sup>32,33</sup>. Significance was obtained by using SigClust<sup>34</sup>. Fisher’s exact test<sup>35</sup> was used to check for associations between clusters and histological subtypes. Gene set enrichment analysis<sup>21</sup> were performed on 69 pulmonary carcinoids and 43 SCLC<sup>2,20</sup> samples; and the gene set oncogenic signatures were used.

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## Acknowledgements

We are indebted to the patients donating their tumour specimens as part of the Clinical Lung Cancer Genome Project initiative. We thank Philipp Lorimier, Elisabeth Kirst, Emilia Müller and Juana Cuesta Valdes for their technical assistance. We furthermore thank the regional computing centre of the University of Cologne (RRZK) for providing the CPU time on the DFG-funded supercomputer ‘CHEOPS’, as well as the support. This work was supported by the Deutsche Krebshilfe as part of the small-cell lung cancer genome-sequencing consortium (grant ID: 109679 to R.K.T., M.P., R.B., P.N., M.V. and S.A.H.). Additional funds were provided by the EU-Framework program CURELUNG (HEALTH-F2-2010-258677 to R.K.T., J.W., J.K.F. and E.B.); by the German federal state North Rhine Westphalia (NRW) and the European Union (European Regional Development Fund: Investing In Your Future) within PerMed NRW (grant 005-1111-0025 to R.K.T., J.W., R.B.); by the Deutsche Forschungsgemeinschaft through TH1386/3-1 (to R.K.T.) and through SFB832 (TP6 to R.K.T. and J.W.; TP5 to L.C.H.); by the German

Ministry of Science and Education (BMBF) as part of the NGFNplus program (grant 01GS08101 to R.K.T., J.W., P.N.); by the Deutsche Krebshilfe as part of the Oncology Centers of Excellence funding program (R.K.T., R.B., J.W.); by Stand Up To Cancer–American Association for Cancer Research Innovative Research Grant (SU2C-AACR-IR60109 to R.K.T.); by an NIH K12 training grant (K12 CA9060625) and by an Uniting Against Lung Cancer grant, and a Damon Runyon Clinical Investigator Award (to C.M.L.); and by AIRC and Istituto Toscano Tumori project F13/16 (to F.C.).

## Author contributions

L.F.-C. and R.K.T. conceived the project. L.F.-C., M.P. and R.K.T. analysed, interpreted the data and wrote the manuscript. L.O., C.M., I.D., B.P., K.K., J.A. and M.B. performed experiments. L.F.-C., M.P. and X.L. performed computational analysis. M.P., R.S. and S.A.H. provided unpublished algorithms. L.F.-C., M.P., T.Z., R.B. and R.K.T. gave scientific input. A.S., O.T.B., A.H., S.S., M.L.-I., S.A., E.S., G.M.W., P.R., Z.W., B.S., J.K.F., R.H., M.P.A.D., L.C.H., I.P., S.P., C.L., F.C., E.B. and R.B. contributed with samples. L.O., W.D.T., E.B. and R.B. performed pathology review. V.A. and U.L. provided and optimized compute and data infrastructure. D.S., F.L., J.G., G.B., P.N., P.M.S., S.A., J.W. and M.V. helped with logistics. All the co-authors reviewed the manuscript.

## Additional information

**Accession codes:** Whole genome sequence data, whole exome sequence data, transcriptome sequence data and affymetrix 6.0 (copy number) data have been deposited at the European Genome-phenome Archive under the accession code EGAS00001000650.

**Supplementary Information** accompanies this paper at <http://www.nature.com/naturecommunications>

**Competing financial interests:** R.K.T. and M.P. are founders and shareholders of Blackfield AG. R.K.T. received consulting and lecture fees (Sanofi-Aventis, Merck, Roche, Lilly, Boehringer Ingelheim, AstraZeneca, Atlas-Biolabs, Daiichi-Sankyo, MSD, Blackfield AG, Puma) as well as research support (Merck, EOS and AstraZeneca). M.P. received consulting fees from Blackfield AG. R.B. is a cofounder and owner of Targos Molecular Diagnostics and received honoraria for consulting and lecturing from AstraZeneca, Boehringer Ingelheim, Merck, Roche, Novartis, Lilly and Pfizer. J.W. received consulting and lecture fees from Roche, Novartis, Boehringer Ingelheim, AstraZeneca, Bayer, Lilly, Merck, Amgen and research support from Roche, Bayer, Novartis, Boehringer Ingelheim. T.Z. received honoraria from Roche, Novartis, Boehringer Ingelheim, Lilly, Merck, Amgen and research support from Novartis. C.M.L. has served on an Advisory Board for Pfizer and has served as a speaker for Abbott and Qiagen. The remaining authors declare no competing financial interests.

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**How to cite this article:** Fernandez-Cuesta, L. *et al.* Frequent mutations in chromatin-remodelling genes in pulmonary carcinoids. *Nat. Commun.* **5**:3518 doi: 10.1038/ncomms4518 (2014).